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Using X-Rays To Test CVD Diamond Detectors For Areal Density Measurement At The National Ignition Facility

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At the National Ignition Facility (NIF), 192 laser beams will compress a target containing a mixture of deuterium and tritium (DT) that will release fusion neutrons, photons, and other radiation. Diagnostics are being designed to measure this emitted radiation to infer crucial parameters of an ignition shot. Chemical Vapor Deposited (CVD) diamond is one of the ignition diagnostics that will be used as a neutron time-of-flight detector for measuring primary (14.1 MeV) neutron yield, ion temperature, and plasma areal density. This last quantity is the subject of this study and is inferred from the number of downscattered neutrons arriving late in time, divided by the number of primary neutrons. We determine in this study the accuracy with which this detector can measure areal density, when the limiting factor is detector and electronics saturation. We used laser-produced x-rays to reproduce NIF signals in terms of charge carriers density, time between pulses, and amplitude contrast and found that the effect of the large pulse on the small pulse is at most 8.4%, which is less than the NIF accuracy requirement of ±10%.

1. Introduction

During ignition attempts at NIF, a large number of primary neutrons (14.1 MeV) will first be emitted from the plasma, followed by the downscattered neutrons (scattered inside the plasma) and then by the scattered neutrons (scattered outside the target). Figure 1 shows the calculated signal in a CVD diamond detector located 20 m from target chamber center[1], for a typical failed ignition attempt (2.1e16 neutrons emitted in 4π). Since the areal density of a DT plasma is proportional to the number of downscattered neutrons divided by that of primary neutrons[2], the main concern of such a measurement is that the large pulse (14.1 MeV primary neutrons) arrives at the detector location 70 ns before the much weaker downscattered neutron pulse (amplitude ratio ≈ 500) and could saturate it, possibly leading to small signal measurement errors at a level greater than the ±10% NIF accuracy requirement. We have previously demonstrated[3] that CVD diamonds are radiation hard and fast enough to measure the large number of primary neutrons emitted during an ignition attempt (10^{16} - 10^{19} neutrons in 4π). This present work studies the accuracy of such a measurement.

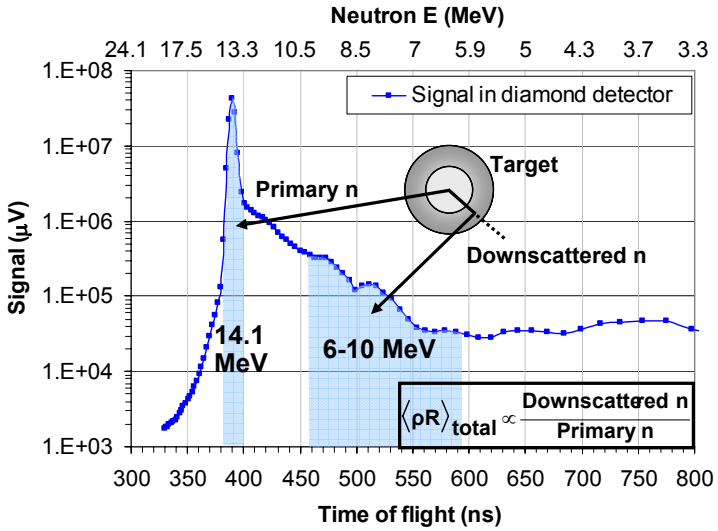

Figure 1. Simulated signal in a Ø1cm x 1mm CVD diamond detector at 20m from the target, from a typical failed ignition shot (2.1E16n in 4π)

2. Methods and experimental setup

We used two laser beams from the Jupiter Laser Facility at the Lawrence Livermore National Laboratory to produce a large x-ray pulse followed 70 ns later by a small pulse similar to NIF signals in terms of charge carriers

density and amplitude contrast. Fig. 2 is a drawing of the experimental set-up. The large energy laser beam had up to 5.5 J of energy, 500 fs of pulse duration, and less than 50 μm of spot diameter, corresponding to an intensity of about 5e17 W/cm^2. The small energy beam had an energy of up to 450 mJ, the same pulse duration and spot diameter as the large energy beam, corresponding to an intensity of about 5e16 W/cm^2.

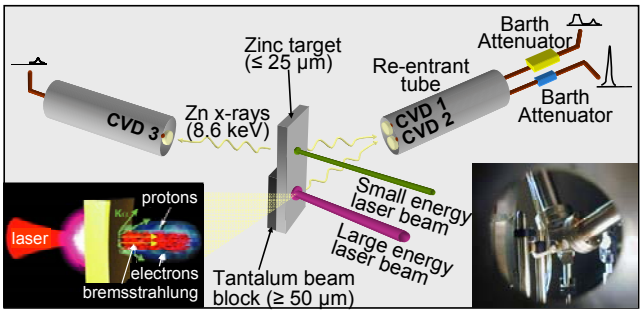

Figure 2. System of 3 CVD diamond detectors measuring a large x-ray pulse followed by a small pulse.

The target was a 25 μm foil of zinc with a 50 μm foil of tantalum glued on the lower back part of the target. The emitted x-ray spectrum was formed mainly by the Zn k_α peak (8.62 keV) and a smaller k_β peak (9.57 keV) on top of a bremsstrahlung spectrum. The thickness of the tantalum foil was chosen to be several times the mean free path of a 8.6 keV x-ray (4.26 μm) so that a large number of the x-rays produced in the zinc foil by the large energy beam were absorbed in the tantalum foil. This target allowed the detector, CVD3, to receive only x-rays created by the small energy beam (thus the small pulse), and not the large pulse. Two other detectors, CVD1 and CVD2 viewed the front side of the target and consequently received both large and small x-ray pulses. Each detector was connected to an individual oscilloscope channel, allowing different channel settings. CVD1 was set to record both large and small pulses, but viewing the small pulse required the large pulse to be clipped. Consequently, no information about the large pulse was recorded by CVD1. CVD2 was set to record the large pulse only, loosing any information about the small pulse, by using a Barth attenuator (up to an attenuation of 40) and a voltage per division appropriate to obtain the entire large pulse on the oscilloscope screen. An earlier calibration of both detectors permitted us to calculate the amplitude of the large pulse on CVD1, and as a result the contrast ratio between that large pulse and the recorded small pulse.

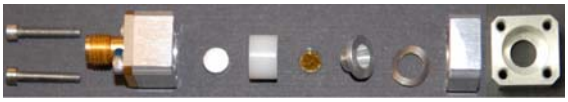

Figure 3. CVD diamond detector (golden disk) and its casing.

The oscilloscope used was a Tektronix TDS684B with a 1 GHz bandwidth and a 5 GHs sampling frequency. One Picosecond Pulse Labs bias-tee, model 5531, was used per channel. The high voltage power supply was a Stanford Research Systems, Inc., model PS325/2500V-25W, and was delivering +1000V. Oscilloscope, high voltage power supply, Barth attenuators, and bias-tees were all enclosed in a copper faraday cage to protect the electronics from electromagnetic pulses (EMP). The cables connecting the faraday box to the detectors were RG142 cables that shielded the signal from the EMP. Earlier tests using RG316 cables showed large EMP. SMA connectors were used on the electronics, on cables, and on detectors. The detectors were placed in 2 re-entrant tubes sealed from the chamber vacuum with a 686 μm Be window that transmitted roughly 90% of the x-rays. The detectors were Ø0.5 cm x 300 μm polycrystalline CVD diamond wafers made by Harris International, covered on both sides by a Ø0.4 cm x 1 μm gold electrode, with a very thin layer of titanium as a binding layer between the diamond and the gold. Both wafer and aluminum casing are showed on Fig. 3.

3. Results and discussion

During a typical failed ignition attempt (2.1E16 n yield) and with a Ø0.5 cm x 300 μm CVD diamond crystal, we expect to record a large 14.1 MeV neutron pulse whose integral is about 50 V.ns (this number scales with the active area of the detector). The downscattered neutrons arrive 70 ns later creating a signal with an amplitude about 500 smaller than that of the primary neutrons.

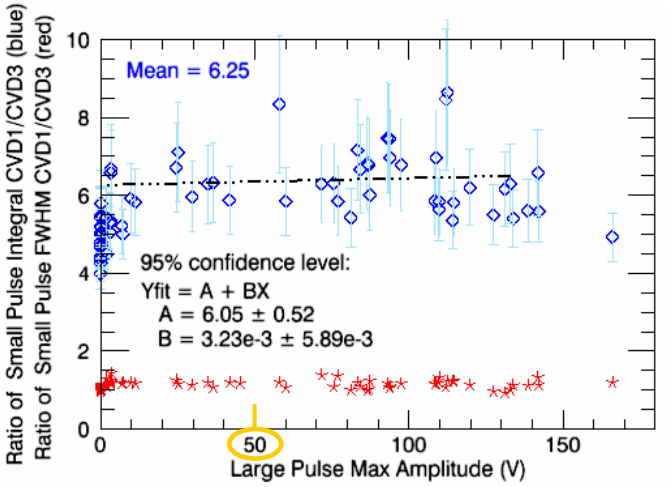

Figure 4. Small pulse integral (blue diamonds) and FWHM (red stars) versus the amplitude of the large pulse.

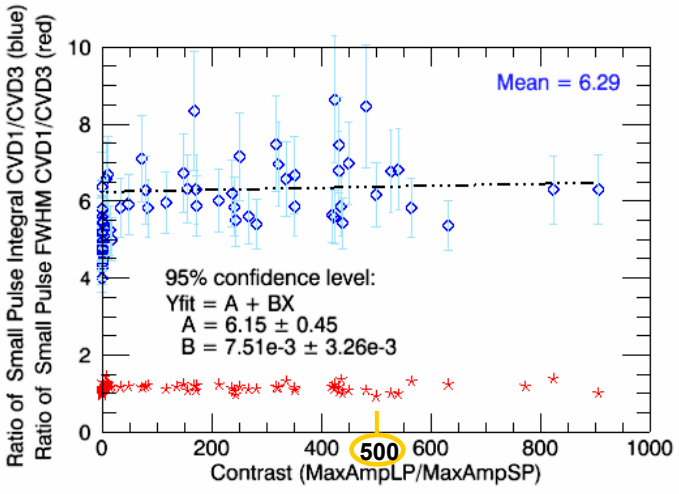

Figure 5. Small pulse integral (blue diamonds) and FWHM (red stars) versus the amplitude contrast of the large pulse by the small pulse.

We obtained contrast in amplitude of up to 900 in our Ø0.5 cm x 300 μm CVD diamond detectors, which is well above the expected contrast of 500. We also produced large pulses of up to 170 V.ns, also well above the expected 50 V.ns. The results of the integral versus the amplitude of the large pulse (blue diamonds in Fig. 4) gives the amount of charge measured by the detector and corresponds to how the integral of the downscattered neutron signal will be modified depending on the amplitude of the large pulse. If the detector were to saturate, this amount of measured charge would decrease leading to a downward slope in the curve of the integral of CVD1/CVD3. We can see that up to about 120 V, the fitting curve (dotted line) stays straight with a upward slope of about 0.32% and a standard deviation of 0.52, and then decreases. This latter decrease is not due to saturation but is due to the fact that the charge collection in a CVD diamond starts to decrease when the measured voltage is above 10% of the applied voltage (1000V). The error bars were calculated taking into account the resolution of the oscilloscope, the background subtraction method, and the counting statistics. We see that in the region of interest, below 120V, the deformation of the small pulse by the large pulse is negligible within the 8.4% experimental error (standard deviation divided by the mean), and this is within the 10% NIF requirement.

When there is no large pulse preceding the small pulse or when the laser energy of the large pulse is low (blue diamonds on the left in Fig. 4&5), the value of the integral is lower than it is for higher large pulse amplitude values. The reason of this drop in signal is unclear but is probably related to changes to the rear target surface caused by the large pulse striking the front surface 70 ns earlier. This is more than enough time for a shock wave to transit

the target and eject material from the back surface, so that the small pulse interacts with a density gradient rather than with a solid surface. The Full Width at Half Maximum (FWHM, red stars) is also constant over the large pulse amplitude range. Both results indicate that for large pulses of up to about 120 V.ns, within statistical fluctuations, the detector system has time to recover completely before measuring the small pulse, and consequently there is an insignificant deformation of the small pulse due to the effect of the large pulse.

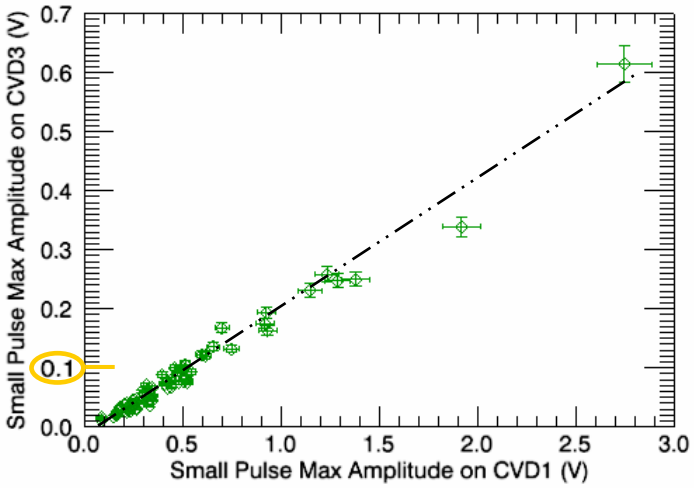

Figure 6. Small pulse amplitude in CVD3 (no preceding large pulse) versus that in CVD1 (preceding large pulse).

We note that the ratio of the integrals in Fig. 4 is about 6.25, and not 1 because the x-ray flux reaching the detector viewing the back of the target (CVD3) is about 6 times smaller than that reaching the front detectors (CVD1 and CVD2). Fig. 6 shows the amplitude of the small pulse in CVD3 versus in CVD1, a curve that should be linear until saturation effects are recorded in CVD1, at which point the line should curve upward (apparent loss of signal in CVD1). During a typical failed ignition shot, we can expect to record a 100 mV small pulse (500 times less than 50 V.ns with a FWHM of about 1.2ns), and in this voltage range the points in Fig. 6 deviate from linearity by 5% or less, which again is well within the 10% NIF accuracy requirement.

4. Conclusion

In this work, low-energy x-rays were used to reproduce NIF signals in terms of charge carrier density and contrast between a large pulse arriving 70 ns before a smaller pulse. Since the areal fuel density is proportional to the number of downscattered neutrons divided by the number of primary neutrons, saturation effects due to the primary neutrons set a measurement accuracy limit that needs to be within 10%. We find that CVD diamond detectors and their associated electronics recover fast enough to record the downscattered neutron signal with an accuracy better than 10%. Other sources of measurement error, including background signals and EMP effects, will set the ultimate limit on the accuracy with which we can expect to measure fuel areal density with CVD diamonds.

Acknowledgments

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[3] L. Dauffy, J. Koch, N. Izumi and R. Tommasini, Rev. Sci. Inst. 77 (10), (2006).